

Counting Houses of Pareto Optimal Matchings in the House Allocation Problem

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Abstract

In an instance of the house allocation problem two sets A and B are given. The set A is referred to as *applicants* and the set B is referred to as *houses*. We denote by m and n the size of A and B respectively. In the house allocation problem, we assume that every *applicant* $a \in A$ has a preference list over the set of houses B . We call an injective mapping τ from A to B a matching. A *blocking coalition* of τ is a non-empty subset A' of A such that there exists a matching τ' that differs from τ only on elements of A' , and every element of A' improves in τ' , compared to τ , according to its preference list. If there exists no blocking coalition, we call the matching τ a *Pareto optimal matching* (POM).

A house $b \in B$ is *reachable* if there exists a Pareto optimal matching using b . The set of all reachable houses is denoted by E^* . We show

$$|E^*| \leq \sum_{i=1, \dots, m} \left\lfloor \frac{m}{i} \right\rfloor = \Theta(m \log m).$$

This is asymptotically tight. A set $E \subseteq B$ is *reachable* (respectively *exactly reachable*) if there exists a Pareto optimal matching τ whose image contains E as a subset (respectively equals E). We give bounds for the number of exactly reachable sets. We find that our results hold in the more general setting of multi-matchings, when each applicant a of A is matched with ℓ_a elements of B instead of just one. Further, we give complexity results and algorithms for corresponding algorithmic questions. Finally, we characterize *unavoidable* houses, i.e., houses that are used by all POM's. This yields efficient algorithms to determine all unavoidable elements.

1 Introduction

1.1 Definitions

The house allocation problem is motivated by the following setup: a set of people is interested to be allocated to a certain set of houses. Each person has a ranking over the set of houses and wants to be assigned to the house with her highest preference. As soon as two people have the same favorite house this is not possible. Motivated by this picture we abstract the set up and start with some definitions.

In an instance of the house allocation problem two sets A and B are given. The set A represents applicants and the set B represents houses. We denote by m and n the size of A and B respectively. In the house allocation problem, we assume that every $a \in A$ has a preference list over the set B . A preference list can be formally defined as a total order of B . We call an injective mapping τ from A to B a *matching*. A *blocking coalition* of τ is a non-empty subset A' of A such that there exists a matching τ' that differs from τ only on elements of A' , and every element of A' improves in τ' , compared to τ according to its preference list. If there exists no blocking coalition, τ is called a *Pareto optimal matching* (POM).

We represent the preference lists by an $m \times n$ matrix. Every row represents the preference list of one of the applicants in A , i.e., in a given row r corresponding to some applicant $a \in A$, the leftmost house is the one that a prefers most, etc., that is house b_1 is left to b_2 in r if and only if a prefers b_1 over b_2 . Note that no row contains an element from B twice. We usually denote this matrix by M and following this interpretation we usually denote the members of A by r_1, r_2, \dots, r_m and the members of B by $1, 2, \dots, n$. Because of this matrix representation, we usually refer to members of A only as rows and to members of B as elements (of the matrix).

To illustrate the notion consider the following matrix and observe that the matching indicated by circles is indeed Pareto optimal.

$$\begin{pmatrix} \textcircled{1} & 5 & 3 & 2 & 4 \\ 3 & 1 & \textcircled{4} & 5 & 2 \\ 1 & \textcircled{3} & 5 & 4 & 2 \end{pmatrix}$$

We denote tuples $p = (a, k)$ as positions of the matrix, if a is some row and k is some natural number. A matching corresponds to a set of positions P_τ if there is exactly one position for each row and no two positions contain the same house. The image set of τ corresponds to the set of houses of B in these positions. Thus, we say that τ *selects* some position p of M (resp. some element b of B), if p is in P_τ (resp. b is in the image set of τ). Similarly, given some matching τ we say that a row a *selects* a position p in row a (resp. element b) if $p = (a, k) \in P_\tau$ for some k (resp. b is in the image of τ). We denote by $s(\tau)$ the image set of τ .

In a POM the positions after the m -th column will never be assigned, because at least one of the previous m elements in that row is preferred and not assigned

to any other element on A . Therefore it is sufficient to consider only $m \times m$ square matrices. (In other words, only the first m elements of the preference lists matter.)

If some POM τ selects p (resp. b), then it is a *reachable* position (resp. *reachable* element). More generally, a set $E \subseteq B$ is (*exactly*) *reachable* if there exists a POM τ with $E \subseteq s(\tau)$ ($E = s(\tau)$). In this case we also say that τ reaches E . An element b is *unavoidable* if it belongs to the set $s(\tau)$ for every Pareto optimal matching τ of M and b is called *avoidable* if there exists a Pareto optimal matching τ with $b \notin s(\tau)$. A set E is *avoidable* if there exists a POM τ with $s(\tau) \cap E = \emptyset$. Note that for a set E such that $|E| = m$ it is exactly reachable if and only if $B \setminus E$ is avoidable. These notions can be generalized naturally to the case of *multi-matchings*, when each element a has to be paired up with $\ell_a \geq 1$ elements of B . For the precise definitions see Section 5. These *Pareto Optimal Multi-matchings* (POMMs) can also appear naturally in practical applications and we will see that our results about POMs generalize naturally to POMMs. We will also study matrices with fewer than m columns, precise definitions will be given in Subsection 1.4. In this case preference lists are incomplete, i.e., it can happen that some elements of A are not assigned. (In this case, it might be interesting to compute a POM of maximum size.)

Example 1. To illustrate the notions and to avoid confusion, we give here a detailed example. The reader can use it to verify that she understood all important notions. The example can be skipped, as we will not refer to it again. Consider the following matrix.

$$M = \begin{pmatrix} 1 & 5 & 3 & 2 \\ 3 & 1 & 5 & 4 \\ 1 & 6 & 5 & 4 \\ 3 & 6 & 2 & 4 \end{pmatrix}$$

The elements 1 and 3 are unavoidable, as they are both in the first column of M and thus picked by every POM. A quick check reveals that every other element of M can be avoided. Each set E with $1 \in E$ or $3 \in E$ is also unavoidable. A simple argument reveals that every set $E \subseteq \{2, 4, 5, 6\}$ with $|E| \geq 3$ is unavoidable, because every POM picks 4 elements of M . In order to determine all unavoidable sets, there remain only six sets $E \subset \{2, 4, 5, 6\}$ of size 2 to be examined. It turns out that only $\{5, 6\}$ and $\{2, 5\}$ are unavoidable.

It is easy to see that all elements of M are reachable. In order to specify the reachable sets note that if some set E is reachable then also all its subsets. Thus it is sufficient to specify all reachable sets of size 4. Also note that if $E \subseteq \{1, 2, 3, 4, 5, 6\}$ of size four is reachable then $D = \{1, 2, 3, 4, 5, 6\} \setminus E$ is avoidable. Thus, by the discussion above, the four reachable sets of size four are exactly

$$\{1, 3, 4, 5\}, \{1, 3, 2, 5\}, \{1, 3, 2, 6\}, \{1, 3, 5, 6\}.$$

1.2 Results

1.2.1 Enumerating reachable elements and sets

In Section 2 we deal with enumerative problems related to reachable elements. Our main result here is the following.

Theorem 2. *Let M be an $m \times m$ matrix and E^* be the set of all reachable elements. Then*

$$|E^*| \leq \sum_{i=1}^m \lfloor m/i \rfloor \leq m(\ln m + 1).$$

This improves the trivial upper bound of m^2 which appears in [11]. In [11] the authors also showed a lower bound construction which has asymptotically as many reachable elements as is implied by our upper bound. Thus Theorem 2 is asymptotically tight.

Denote by $\mathcal{E}(M)$ the family of all (exactly) reachable m -element sets of M . For example, if all the elements in the first column of M are distinct, then $|\mathcal{E}(M)| = 1$. With Theorem 2 we can bound $\mathcal{E}(M)$.

Corollary 3. *For any matrix M , we have $|\mathcal{E}(M)| \leq \binom{m(\ln m + 1)}{m}$.*

This is the only non-trivial upper bound that we found, improving $\binom{m^2}{m}$ of [11]. As an important consequence, our upper bound also improves the upper bound on the pattern matching problem regarded in [11]. The best known lower bound is $\binom{m}{\lceil m/2 \rceil}$ [11]. The construction in that paper is a matrix where in the first $\lfloor m/2 \rfloor$ columns the i -th column contains only element i and in the $(\lfloor m/2 \rfloor + 1)$ -st column there are m different elements which are also all different from $1, 2, \dots, \lfloor m/2 \rfloor$.

1.2.2 Characterization of avoidable elements and sets

Section 3 concentrates on the notion of avoidable elements. Let x be an element suspect to be avoidable. Given some set of rows R we denote by $E_x(R)$ the set of elements left of x in the rows R (i.e., y is in $E_x(R)$ if and only if there exists a row $r \in R$ in which y appears to the left of x ; if x does not appear in r then all elements in r are regarded to be left of x).

Theorem 4. *An element x of a matrix M is avoidable if and only if for every set R of rows of M , we have:*

$$|E_x(R)| \geq |R|$$

Extremal results and algorithmic results in connection to avoidable elements are included in Section 3, as they follow from the proof of Theorem 4. We prove that:

Corollary 5. *Deciding whether an element x is avoidable can be done in $O(m^2\sqrt{m+n})$ and also in $O(m^3)$ time. Listing all unavoidable elements can be done in $O(m^2n\sqrt{m+n})$ and also in $O(m^5)$ time.*

Both results follow from an easy reduction to matchings in a bipartite graph.

1.2.3 Complexity of reachability

Computational questions about reachable elements are considered in Section 4. Among the computational questions connected to the notions defined in this paper, we selected those that we found natural and canonical. The problems are defined as follows:

Problem 1. (*Deciding Reachability*)

Input: A matrix M and a set $D \subseteq B$.

Question: Is D reachable?

Problem 2. (*Deciding Exact Reachability*)

Input: A matrix M and a set $E \subseteq B$

Question: Is E exactly reachable?

Problem 3. (*Counting Reachable Sets*)

Input: A matrix M .

Question: How many sets $D \subseteq B$ are reachable?

Problem 4. (*Counting Exactly Reachable Sets*)

Input: A matrix M .

Question: How many sets E are exactly reachable?

Problem 5. (*Counting Exactly Reachable Supersets*)

Input: A matrix M and some set $D \subseteq B$.

Question: How many sets E with $D \subseteq E \subseteq B$ are exactly reachable?

The next table summarizes our findings about algorithmic questions. The general case is always the same as with 3 column matrices. The hardness results for Problems 1 and 5 already hold if D contains exactly 1 element. It was already observed by Henze, Jaume and Keszegh that Problem 1 is NP-complete [11]. Our contribution among others is to show NP-completeness also for matrices with only 3 columns. The running time of Problem 2 follows from the discussion in Section 3 and Corollary 5.

Problem	2 columns	proof	3 columns	proof
1)	polynomial	(Thm. 13)	NP-complete	(Thm. 10)
2)	polynomial	(Cor. 5)	polynomial	(Cor. 5)
3)	explicit formula	(Thm. 14)	?	
4)	#P-complete	(Thm. 15)	#P-complete	(Thm. 15)
5)	#P-complete	(Thm. 15)	#P-complete	(Thm. 10)

It remains an open question whether Problem 3 is hard for general matrices. We conjecture it is already #P-complete for 3 column matrices.

Problem 4 is a special case of Problem 5 for the case that $D = \emptyset$.

1.3 Motivation and related work

Pareto optimal matchings are one of many concepts to define a 'good' matching in a graph with preference lists. The graph properties and the preference lists

depend on the precise situation they are supposed to model. Most research in this area is driven by economic applications. A recent book on matchings under preferences, by David Manlove [13] contains a broad overview over the field and usually puts a focus on algorithmic rather than economic questions. In this paper we tried, whenever applicable, to follow the notation therein.

A field that evidently seems to be related to our topic is that of stable matchings. This field is very broad and belongs to economic game theory. The seminal work of Gale and Shapley is the starting point for this field [9]. Some work in this field and different variations of the problem can be found in the Ph.D. thesis of Sandy Scott [17], recent papers can be found in the proceedings of the Second International Workshop on Matching Under Preferences called MATCH UP [6]. In these works there are many different concepts of preferences and stability and they ask for efficiently computable solutions that maximize the outcome for the participants in one way or the other. Readers interested more broadly in the topic of algorithmic game theory are referred to the book edited by Nisan, Roughgarden, Tardos and Vazirani [14].

In contrast to most research done in these areas, our question is more combinatorial in nature. The underlying algorithmic question of computing a Pareto optimal matching can be solved by the greedy algorithm. Thus, instead of existence questions, rather the enumerative questions become interesting. (Note that it is non-trivial to compute POMs with extra features.) Nevertheless, for the early definition of stability many authors have tried to establish upper and lower bounds on the number of stable matchings and some combinatorial structures have been unfolded. See [13, Section 2.2.2] for an overview of results in this direction.

Some complexity results similar to ours have been found earlier. The first dates back to 2005 [1]. Their main result is an efficient algorithm to compute a POM with maximum cardinality. Here the preference lists are incomplete. (See Section 1.4 for precise definitions of incomplete preference lists.) Additionally, they show hardness to compute a minimum POM. This result has already some ideas of the proof of Theorem 4. Further the proof of Theorem 15 implies hardness of computation about minimum matchings. Although they show an easy 2-approximation, it is open whether there exists a PTAS for a minimum POM.

We are aware of four recent papers that considered similar results to our complexity results [16, 3, 4, 7]. Their main motivation is to study the behavior of the randomized serial dictatorship also called randomized priority allocation. The randomized serial dictatorship picks a permutation at random and thereafter computes the corresponding greedy matching.

The first paper is by Sabán and Sethuraman [16]. Their results, reformulated in our context, is NP-hardness of Problem 1, for arbitrary matrices. Aziz, Brandt and Brill [3] show #P hardness for a variant of Problem 5 for arbitrary matrices. We improve these results, as we can show this holds also for matrices with only 3 columns. Aziz and Mestre show that constraint versions are solvable in polynomial time [4]. Cechlárová et al. [7] consider a generalized setting: they show NP-hardness of computing a minimum maximal matching even for

matrices with 2 columns by an elegant reduction from vertex-cover very similar in spirit to the proof in Theorem 15.

This work is originally motivated by a work that was presented at the EuroCG 2012 in Braunschweig [11]. See also the follow up work [5]. The authors considered a generalisation of Voronoi diagrams under the assumption that not just one point, but many points are matched in a way that minimizes the sum of the squares of distances between matched points. From the definitions in their paper, the Pareto optimality comes as a natural property. They asked explicitly for the number of exactly reachable sets, as it gives an upper bound on the number of Voronoi cells in the above setting. Motivated by this, they gave lower and upper bounds on the number of exactly reachable stable sets. To do this, first they gave lower and upper bounds for the number of reachable elements. In this paper we improve their upper bound for the number of reachable elements and by that we prove that their lower bound is asymptotically correct. This also yields a significant improvement on the previous upper bound on the number of exactly reachable stable sets, although in this case our new upper bound still does not meet the lower bound they had. Their work is based on a work by Rote presented at the EuroCG 2010 in Dortmund [15].

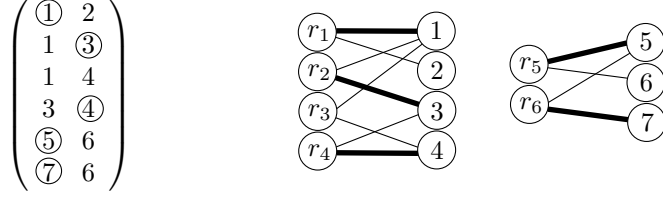
1.4 Preliminaries

As we also want to study matrices with fewer than m columns, we need to define what we mean by a matching under these assumptions. There are two equivalent ways. First, we could say that every row, for which all elements are already picked by other rows, just does not get assigned to anything. A second and nicer way is to add columns, with all elements in one column being the same and not appearing before. If we want to know whether some set E is exactly reachable in the first way, we construct E' from E by adding the elements from the first $m - |E|$ additional columns (and vice versa). The following is an example of a 2 column matrix.

$$\begin{pmatrix} 1 & 4 \\ 2 & 1 \\ 2 & 5 \\ 4 & 3 \end{pmatrix} \sim \begin{pmatrix} 1 & 4 & c_1 & c_2 \\ 2 & 1 & c_1 & c_2 \\ 2 & 5 & c_1 & c_2 \\ 4 & 3 & c_1 & c_2 \end{pmatrix}$$

We use the first approach. However, using the second approach, some hardness results will carry over from 2 or 3 column matrices to k column matrices ($2 \leq k \leq m$). In such a case, we will point this out again at the appropriate places.

To see the correspondence between matchings in a graph-theoretical sense and in our context we define the *bipartite row element graph* G as follows. The vertices are defined as the set of rows and elements; an element e is adjacent to some row r if and only if e appears in r . See an example for the special case of a matrix with only 2 columns.



The circled POM corresponds to the thick matching on the right side.

If there is no blocking coalition of size $\leq i$, we call the matching an *i-Pareto optimal matching* (*i-POM*). In particular this implies that every POM is an *i-POM*. We call a matching *1-POM* if there is no blocking coalition of size one. The next matching is 1-Pareto optimal but not Pareto optimal.

$$\begin{pmatrix} 1 & \textcircled{5} & 3 \\ 5 & 1 & \textcircled{4} \\ 5 & \textcircled{1} & 2 \end{pmatrix}$$

Observation 6. *If τ is a POM and τ selects position p in row a , then τ selects every element that appears in row a left of p .*

This observation also holds for 1-POMs. A matching τ is *greedy* if there exists a permutation π of A such that the matching can be generated in the following manner: we process the rows of M in the order determined by π , and in each row we pick the leftmost element that was not picked earlier. Given some permutation π we call the corresponding greedy matching τ_π .

In the literature, the mechanism of determining a matching from a permutation is called *Serial Dictatorship Mechanism*.

Lemma 7 brings all the introduced notions together, showing that POM, 1-POM and greedy matchings select exactly the same sets.

Actually, POM and greedy matchings are equivalent notions, as proven in [1, 11, 18], and probably also by many others.

For the proof of the next lemma we need an equivalent definition of POM. Assume $\tau_1 \neq \tau_2$. We say τ_1 is *better than* τ_2 if every element $a \in A$ is matched in τ_1 to a better or equally good element than in τ_2 , according to the preference list of a . POM are exactly the maximal elements with respect to this *better than* relation.

Lemma 7. *Let $E \subseteq \{1, \dots, n\}$ with $|E| = m$. The following statements are equivalent.*

1. *E is (exactly) reachable, i.e. there exists a POM τ with $s(\tau) = E$.*
2. *There exists a permutation π such that for the greedy matching τ_π we have $s(\tau_\pi) = E$.*
3. *There exists a 1-Pareto optimal matching (1-POM) τ with $s(\tau) = E$.*

Proof. [1 \Rightarrow 2] Let τ be a POM matching such that $s(\tau) = E$. We construct a permutation π inductively. If possible take as the next row, in the order of our permutation, the one that has a position of τ in its first entry. Delete the element a at this position from all other rows and continue. We show that at each stage there must be such a row. For the purpose of contradiction assume such a row does not exist. Take any row, denoted by q_1 and let e_1 be some element which is left to the element selected by τ in row q_1 . Because τ is Pareto optimal, there exists some row r_2 selecting e_1 . Let e_2 be any element left to e_1 in row r_2 . In this way we can define a sequence (e_i) and (r_i) . As we have only finitely many elements, at some point we get a first e_j that appears earlier in the sequence $e_i = e_j$, $i < j$. This implies that in the rows r_i, \dots, r_j we can improve simultaneously (i.e., it is a blocking coalition), which is a contradiction to the assumption that τ is Pareto optimal.

[2 \Rightarrow 3] As every row picks the best element, not yet selected, it is clear that no single row can improve.

[3 \Rightarrow 1] Let τ_0 be some 1-Pareto optimal matching and $E = s(\tau_0)$. Observe that all the elements left to the elements picked by τ_0 are in E . The set of matchings that are better or equal to τ_0 is non-empty as it contains τ_0 and the set is of course finite, so there exists a best matching τ_1 among them, i.e. one for which there is no better matching. This must be a POM and by Observation 6 we have $s(\tau_1) \subseteq s(\tau_0) = E$, and the size of $s(\tau_1)$ is also m . This implies $s(\tau_1) = E$. \square

Note that this lemma implies that also for any i , i -POMs select the same sets as POMs/1-POMs. Note also that the proof of Lemma 7 implies that actually every POM matching is greedy. The inverse is also true and left as an exercise, as we will not use it later.

2 Counting reachable elements and sets

We start with a discussion of reachable positions. For every row r , there exists a reachable position p_r furthest to the right in that row, we call such a position *last reachable*. However not all positions left of the last reachable position must be reachable. Consider for example the following matrix together with the matching τ indicated by circles.

$$\begin{pmatrix} \textcircled{5} & 4 & 3 & 2 \\ 5 & \textcircled{1} & 6 & 7 \\ 1 & \textcircled{2} & 8 & 9 \\ 2 & 1 & 5 & \textcircled{4} \end{pmatrix}$$

The matching τ is Pareto optimal and thus the circled position in the bottom row with element 4 is the last reachable position in that row. However, it is easy to verify, that the two positions left to this circled position (with elements 1 and 5) are not reachable.

Theorem 2. *Let M be an $m \times m$ matrix and E^* be the set of all reachable elements. Then*

$$|E^*| \leq \sum_{i=1}^m \lfloor m/i \rfloor \leq m(\ln m + 1).$$

Proof. Let T be some set of k POMs of M . We denote by $E(T)$ the set of elements reached by at least one POM of T . (formally: $E(T) = \bigcup_{\tau \in T} s(\tau)$.) We claim:

$$|E(T)| \leq \sum_{i=1}^k \lfloor m/i \rfloor.$$

Note

$$\sum_{i=1}^k \lfloor m/i \rfloor \leq \sum_{i=1}^m \lfloor m/i \rfloor \leq m(\ln m + 1).$$

Because $\lfloor m/i \rfloor = 0$ for $i > m$ and the known bound on the harmonic series. Thus the theorem follows from the claim.

The proof goes by induction on k . The base case $k = 1$ is true as one POM selects exactly m different elements.

Consider now a set T of $k \geq 2$ POMs and the set of positions reached by T . Among these positions we denote by p_i the position furthest to the right in row i and we denote $F = \{p_1, \dots, p_m\}$. We say that an element e (resp. position p) is uniquely reachable by some τ if τ is the only POM in T that reaches e (resp. selects p). Consider the set $G \subseteq F$ of those rightmost reachable positions that are reachable by exactly one POM of T . By the pigeon-hole principle there exists a POM τ in T that reaches at most $1/k$ portion of G . Denote the set of elements in these positions by H ($|H| \leq \lfloor m/k \rfloor$).

By the definition of H all elements $s(\tau) \setminus H$ are not selected uniquely by τ , i.e. some other matching of T also selects it.

Let us explain this in more detail. Consider an element $e \in s(\tau) \setminus H$ and denote by p the position of e . As $p \notin G$ there exists another matching $\tau' \neq \tau$ that either also selects p or τ' selects a position further to the right of p in the same row. In both cases holds: τ' must select e by Observation 6.

Thus the rest of the reached elements are also reachable by $T \setminus \tau$. By induction we get

$$E(T) \leq E(T \setminus \tau) + \lfloor m/k \rfloor \leq \left(\sum_{i=1}^{k-1} \lfloor m/i \rfloor \right) + \lfloor m/k \rfloor = \sum_{i=1}^k \lfloor m/i \rfloor. \quad \square$$

A natural question is, if we could asymptotically improve upon the bound given in the previous Theorem 2. The following construction by Henze, Jaume and Keszegh [11] shows asymptotic tightness.

The following example has more rows than columns, however the rows can be filled with arbitrary elements as none of these elements are reachable anyway.

Example 8 ([11]). For each k , a matrix M_k with $m = 2^k$ rows and $(m/2) \log 4m = (k+2)2^{k-1}$ reachable elements is constructed recursively as follows.

$$M_0 = \begin{pmatrix} 1 \end{pmatrix};$$

and, for $k \geq 0$,

$$M_{k+1} = \left(\begin{array}{c|c} 1 & \\ \vdots & M'_k \\ 2^k & \\ \hline 1 & \\ \vdots & M''_k \\ 2^k & \end{array} \right),$$

where M'_k and M''_k are relabelings¹ of M_k with no common element and all elements different from $1, 2, \dots, 2^k$. The undefined entries of the matrix can be chosen arbitrarily.

Regarding the claim in the proof of Theorem 2, we prove that it is tight for certain values of k and m :

Corollary 9. *For every k there exists a matrix N_k with $m = k!$ rows and a set T_k of k POMs, such that the number of elements reached by T_k is exactly $\sum_{i=1}^k m/i$.*

Proof. The construction is again recursive. For each k we define the matrix N_k with $m = k!$ rows and k columns with the property that each element appears only in one column, and each element that appears in the j th column ($j \leq k$), appears there exactly $k-j+1$ times. We also define a set Π_k of k permutations of the $k!$ rows from which we get T_k by taking the greedy matchings corresponding to the permutations. We will prove that all the elements of N_k are reachable by some greedy matching of T_k .

The matrices N_k are defined in the following way:

$$N_1 = \begin{pmatrix} 1 \end{pmatrix},$$

and for $k \geq 1$:

$$N_{k+1} = \left(\begin{array}{c|c} 1 & \\ \vdots & N_k^1 \\ k! & \\ \hline \vdots & \vdots \\ 1 & \\ \hline \vdots & N_k^{k+1} \\ k! & \end{array} \right).$$

¹ A matrix M' is a *relabeling* of a matrix M if there is a bijective function between the elements (not positions!) of M and M' such that applying this function to the elements in all the positions of M we get M' . Clearly two matrices that are relabelings of each other are equivalent from our perspective.

Here $N_k^1, N_k^2, \dots, N_k^{k+1}$ are $k+1$ matrices which are all relabelings of N_k without common elements and no matrix N_k^i contains an element from the set $\{1, 2, \dots, k!\}$. It is clear that N_{k+1} has $(k+1)!$ rows and $k+1$ columns. Moreover, each element in the j th column ($j \leq k+1$) appears there $(k+1) - j + 1$ times: this is clear for the first column, and is easily seen for other columns by induction.

Next we define the permutations. For $k=1$, Π_1 contains the only permutation on the one row of N_1 . Next we recursively define Π_{k+1} . For each N_k^j ($1 \leq j \leq k+1$), we have by recursion an associated set $\{\pi_1^j, \pi_2^j, \dots, \pi_k^j\}$ of k permutations (thus, π_i^j is the i th permutation from Π_k relabeled accordingly to N_k^j – the j th copy of N_k in N_{k+1}). Now the permutations in Π_{k+1} are defined as follows. For every i ($1 \leq i \leq k+1$), the permutation π_i is obtained by taking first the $k!$ rows of N_k^i in any (for example, the natural) order; then the rows of $N_k^1 \cup N_k^2 \cup \dots \cup N_k^{i-1}$ in the order determined by the permutations $\pi_{i-1}^1, \pi_{i-1}^2, \dots, \pi_{i-1}^{i-1}$; and, finally, the rows of $N_k^{i+1} \cup N_k^{i+2} \cup \dots \cup N_k^{k+1}$ in the order determined by the permutations $\pi_i^{i+1}, \pi_i^{i+2}, \dots, \pi_i^{k+1}$. Clearly, each row was taken once, so π_i is indeed a permutation. Also, when processing such a permutation, in the first $k!$ steps we choose all elements $1, 2, \dots, k!$, so in the rest the permutation chooses the same elements in each N_k^j ($j \neq i$) as the corresponding permutation (π_{i-1}^j or π_i^j) would choose in N_k^j .

Thus by induction it is true that these permutations choose all elements of N_k . Indeed, this is true for N_1 and by induction it remains true as for every N_k^j ($1 \leq j \leq k+1$) all π_i^j ($1 \leq i \leq k$) is part of some π_u ($1 \leq u \leq k+1$). Finally, the number of different elements in N_{k+1} is $\sum_{i=1}^{k+1} m/i$, as we have $k+1$ columns, and in the j th column ($1 \leq j \leq k+1$) each element appears $(k+1) - j + 1$ times, thus this column has $\frac{m}{(k+1)-j+1}$ different elements. \square

3 Characterization of avoidable elements

In this section we characterize avoidable elements and sets. Recall that we define $E_x(R)$ as the set of elements left of x in the rows of R (i.e., y is in $E_x(R)$ if and only if there exists a row $r \in R$ in which y appears to the left of x ; if x does not appear in r then all elements in r are regarded to be left of x)

Theorem 4. *An element x of a matrix M is avoidable if and only if for every set R of rows of M , we have:*

$$|E_x(R)| \geq |R|$$

Proof. $[\Rightarrow]$ Let τ be a POM which does not pick x and let R be a set of rows. In each row a different element is picked by τ , which is left of x . This shows the claim.

$[\Leftarrow]$ Without loss of generality x is present in all the rows. Consider the bipartite graph on $A \cup B$, defined by all pairs $(a, b) \in A \times B$ such that b appears in row a before x . The above condition says, that for all subsets $R \subset A$ the neighbourhood of R is larger or equal to R in terms of size.

By Hall's theorem, there exists a matching τ that picks elements to the left of x . We can modify τ so that each row picks an element farthest to the left in M not chosen by any other row. In other words τ is a 1-POM. By Lemma 7 there is a POM τ' selecting the same set of elements as τ , thus τ' does not choose x , and so x is avoidable. \square

Corollary 5. *Deciding whether an element x is avoidable can be done in $O(m^2\sqrt{m+n})$ and also in $O(m^3)$ time. Listing all unavoidable elements can be done in $O(m^2n\sqrt{m+n})$ and also in $O(m^5)$ time.*

Proof. For an element x to be avoidable is equivalent to the existence of a matching that connects all the elements of A with elements left to x . Thus, we need to find a maximum bipartite matching. The fastest known algorithm (Hopcroft-Karp [12]) checks this in $O(\sqrt{V}E)$ time. In our case $|V| \leq m+n$, $|E| \leq m^2$. Thus, it can be checked whether x is avoidable in $O(m^2\sqrt{m+n})$ time. Consequently, listing of all unavoidable elements by checking all the elements of B can be done in $O(m^2n\sqrt{m+n})$ time. The bounds without n follow from the fact that we can limit the number of relevant elements in B easily to m^2 (the number of elements in the first m columns of the matrix). \square

Recall a set X is said to be *avoidable*, if there exists a matching that avoids every element of X . Note that it is possible that all elements of a set are avoidable, while the set itself is not. Theorem 4 extends to set X , by replacing all elements of X by a single element x . If x is avoidable, then X was avoidable and vice versa. (If more than one element of X appears in a row replace only the leftmost one.)

4 Complexity of reachability

In this section we show that Problems 1 to 5 defined in the introduction lie in the indicated complexity classes.

Problem 2 is polynomially solvable, seen as follows: let M be a matrix and E be a set of m elements occurring in the matrix. We define $F := B \setminus E$, then E is exactly reachable if and only if F is avoidable, which can be checked in polynomial time by Corollary 5.

We start with a brief and informal explanation of the class #P. A detailed introduction is given by Arora and Barak [2].

Informally #P is a class of counting problems. Counting problems get an object and count some other objects satisfying some condition. The only restriction is that the size of the binary representation of the number of objects counted is polynomial in the input. But this is given in all that follows, because we have exponential upper bounds on the number of objects to be counted.

Famous examples of #P-complete problems are:

- How many variable assignments does a given boolean formula satisfy?
- How many perfect matchings does a given bipartite graph have?

Note that the decision version of the first problem is NP-hard and of the second problem is in P.

A problem L is defined to be #P-complete if it lies in #P and there exists a polynomial time counting reduction from all other problems in #P to L . Due to transitivity of counting reductions, it is sufficient to reduce one #P-complete problem to L .

Finally, a counting reduction transforms the input of one problem to the input of a second problem in a way that the counting problem for the first problem can be solved via the reduction and the solution to the second problem. It will be very clear in our context, that our reductions are indeed counting reductions.

We will use the result from Creignou and Hermann [8] that #1-in-3-SAT is #P-complete. Here it is asked how many assignments exist such that every clause of a given 3CNF-formula has exactly one true and two false literals. We will also use later, that the corresponding decision problem is NP-complete.

We start our discussion with Problems 1 and 5 for 3-column matrices.

Theorem 10. *Problem 1 (Deciding Reachability) is NP-complete and Problem 5 (Counting Exactly Reachable Supersets) is #P-complete, even when D (the set we want to decide if it is reachable) is a 1-element set and the matrix has only 3 columns.*

We will give a transformation that converts 1-in-3-SAT formulas Φ to matrices M with the special property that the number of good assignments for Φ equals the number of reachable sets containing some special element x . This transformation will reduce 1-in-3-SAT to Problem 1 and #1-in-3-SAT to Problem 5 and thus proves the essential part of Theorem 10.

Lemma 11. *Let Φ be an instance of 1-in-3-SAT. Then there exists a matrix M with some element x such that the 1-in-3-satisfying truth assignments of the variables of Φ are in one-to-one correspondence with the exactly reachable sets E with $x \in E$.*

Proof. Let Φ be of the form $C_1 \wedge C_2 \wedge \dots \wedge C_m$. And each of the clauses C_i is of the form $L_1^i \vee L_2^i \vee L_3^i$, where each literal L_j^i is one of the variables x_1, \dots, x_n or its negation. The matrix M_Φ is defined in Figure 1.

Here a_i, b_i, c_i are only used where indicated. The asterisks mark that any element could stand there. Every x_i and its negation get an element named after them. The same holds for every clause C_i . The literals L_i^j need to be replaced by the corresponding variable element.

Let $F : \{x_1, \dots, x_n\} \rightarrow \{0, 1\}$ be an assignment of the variables such that exactly one literal of each clause in Φ becomes true. We construct the corresponding matching τ_F . The matching τ_F selects x_i whenever F gives it the value 1 and its negation otherwise.

There exists exactly one way to select the element C_i for each i . To see this consider as an example $C = x_1 \vee x_2 \vee x_3$ and assume w.l.o.g. that x_1 is true and x_2 and x_3 are false in assignment F . Then τ_F has already selected $x_1, \bar{x}_2, \bar{x}_3$. Thus C can be selected in the following way, indicated by circles:

$$M_\Phi = \begin{pmatrix} a_1 & x_1 & * & * & & \\ a_1 & \overline{x_1} & * & * & & \\ \vdots & \vdots & & & & \\ a_n & x_n & * & * & & \\ a_n & \overline{x_n} & * & * & & \\ & & & & & \\ b_1 & c_1 & L_1^1 & \overline{L_2^1} & \overline{L_3^1} & C_1 \\ b_1 & c_1 & L_2^1 & \overline{L_1^1} & \overline{L_3^1} & C_1 \\ b_1 & c_1 & L_3^1 & \overline{L_1^1} & \overline{L_2^1} & C_1 \\ & & \vdots & \vdots & & \\ & & & & & \\ b_m & c_m & L_1^m & \overline{L_2^m} & \overline{L_3^m} & C_m \\ b_m & c_m & L_2^m & \overline{L_1^m} & \overline{L_3^m} & C_m \\ b_m & c_m & L_3^m & \overline{L_1^m} & \overline{L_2^m} & C_m \\ C_1 & C_2 & \dots & & C_m & x \end{pmatrix}$$

Figure 1: Illustration of the matrix M_Φ

$$\begin{pmatrix} b & c & x_1 & \overline{x_2} & \overline{x_3} & \textcircled{C} \\ b & \textcircled{c} & x_2 & \overline{x_1} & \overline{x_3} & C \\ \textcircled{b} & c & x_3 & \overline{x_1} & \overline{x_2} & C \end{pmatrix}$$

In the same way all clause labels can be selected and it is possible to select x .

In this manner we get from every satisfying assignment F a matching τ_F selecting x . It is easy to see that τ_F is a 1-POM. And thus there also exists a POM selecting the same set. In this way we get from every satisfying truth assignment a 1-POMs selecting x .

We show that we can get a satisfying truth assignment for every 1-POM τ selecting x . We get a truth assignment by taking x_i to be true if x_i is selected in the first $2n$ rows and x_i false if $\overline{x_i}$ is selected. τ will always select one of x_i and $\overline{x_i}$. Clearly, C_1, \dots, C_m are not taken by the last row. The only way to select C_i is if one of its three literals is assigned to be true and the other two are assigned to be false. Thus this assignment is an 1-in-3-satisfying assignment. \square

Let M be some matrix with the element x . We define a matrix M' with exactly three columns by replacing each row by a block. Let $r = (a_1 a_2 \dots a_m)$

be some row, with $m > 3$. We replace it by the following block b_r :

$$\begin{pmatrix} a_1 & a_2 & \beta_1 \\ \beta_1 & a_3 & \beta_2 \\ \beta_2 & a_4 & \beta_3 \\ & \vdots & \\ \beta_{m-4} & a_{m-2} & \beta_{m-3} \\ \beta_{m-3} & a_{m-1} & a_m \end{pmatrix}$$

The β_i elements are different for every block. If τ is a Pareto optimal matching of M , then there exists a unique Pareto optimal matching τ' in M' that selects in each block the same element as τ in M . To see this correspondence assume element a_i is selected in our row r . Then the elements a_1, \dots, a_{i-1} are selected somewhere else in M . Associate with this matching of M the matching in M' , which in block b_r selects the elements $\beta_1, \dots, \beta_{i-2}, a_i, \beta_{i-1}, \dots, \beta_{m-3}$, consecutively from the top row to the bottom row. In the special case that $i = 1$, $i = 2$, $i = m - 1$ or $i = m$ either the first or the second block of β s will be empty. It is easy to check that this is a Pareto optimal matching of M' and has the above property. Uniqueness follows from the fact that in a block b_r knowing in which row of b_r selects τ' the element that appears also in M determines all the selections in b_r .

In every block at most one element of the original row can be selected by any POM τ' . Every POM τ' in M' that selects in every block exactly one element of the original row corresponds to exactly one POM τ of M . Consider the three column matrix M' of the matrix M in Lemma 11. Clearly, the POMs selecting x in M stand in a one to one correspondence with the POMs in M' selecting x . The next lemma summarizes our discussion.

Lemma 12. *Let Φ be some boolean 3-DNF formula. Then there exists a **three column** matrix M with some element x such that the 1-in-3-satisfying truth assignments of the variables of Φ are in one-to-one correspondence with the exactly reachable sets E with $x \in E$.*

proof Thm 10. #1-in-3SAT is #P-complete. Given a 3-DNF formula Φ , the reduction above gives a 3-column matrix, such that the exactly reachable sets containing x are in a one to one correspondence with the satisfying assignments. Thus also Counting Exactly Reachable Supersets is #P-hard. And as 1-in-3SAT is also NP-complete, deciding Reachability is also NP-hard. Membership to these classes (and thus completeness) follows from the exponential upper (2^{m^2}) bound on the number of possible sets. Thus the binary representation is linear in the size of the input. \square

The natural question to ask is, what happens when there are only **two columns**. Understanding the structure of reachability for 2 column matrices gives many interesting results at once. We consider first Problem 1 (Deciding Reachability) and will see easily from the algorithm that we can find an explicit way to count all reachable sets, for 2 column matrices. The complexity of

counting reachable sets for general matrices remains open. On the other hand, we will see that it is #P-complete to count all exactly reachable sets E already for 2-column matrices.

Theorem 13. *Problem 1 (Deciding Reachability) is in P for 2-column matrices.*

Proof. We assume the bipartite row element graph G is connected, otherwise we treat each component separately. Let m denote the number of rows, D the set of elements we wish to reach, and X the set of elements of G .

It is easy to see, by induction on m , that the number of different elements in G is at most $m + 1$. (This is true for $m = 1$ and at most one new element is added when a new row is added.)

We distinguish two cases.

Case (1) $|X| = m + 1$

Case (2) $|X| \leq m$

In the first case we cannot reach X but we will show that for every avoidable element $x \in X$ we can reach $X \setminus \{x\}$. This implies D is reachable if and only if it does not contain all avoidable elements of this component.

In the second case we will show that X (and subsequently D) can be selected.

In the first case, there is one more element than the number of rows and thus it is clear that at least one avoidable element cannot be selected. Further, the number of vertices is $2m + 1$ and the number of edges is $2m$. This implies that G is a tree. Let x be any avoidable element not in D . We orient all edges away from x in G . Clearly the in-degree of every element is exactly one. For every edge oriented from row r to element e , let r select e . As x is avoidable, it is not in the first column. As all elements, except x is selected there is no 1-blocking coalition. Thus the described matching is a 1-POM, by Lemma 7 there is a POM selecting $D \subseteq X \setminus \{x\}$.

Consider now case 2. As every row is incident to exactly two elements the number of edges is exactly $2m$, and as the number of vertices is at most $2m$, G contains a cycle. Let $r_0, e_0, r_1, e_1, \dots, r_t, e_t$ be our cycle. We assign r_i to e_i . In this way all elements on the cycle are selected.

We will repeat in the following. Pick a row r that has at least one of the elements already selected. Such a row exists because we assume that G is connected. There is at most one element which can be selected by r . Let r select this element if possible.

This procedure leads to a matching τ that selects all elements and thus τ is automatically 1-POM, by Lemma 7 there is a POM selecting $D \subseteq X$.

All the above steps are computationally easy. \square

Let M be a 2 column matrix. We assume the corresponding bipartite row element graph has k components. Denote with a_i the number of avoidable elements E_i of the i th component and u_i the number of unavoidable elements F_i . Recall that it is easy to check if an element is avoidable by Corollary 5. Further χ_i is the indicator variable for the event that the i th component is a tree. Recall that every subset of a reachable set is reachable.

Theorem 14. *With the notation and assumptions above:*

$$|\{E : E \text{ is reachable}\}| = \prod_{i=1}^k (2^{a_i} - \chi_i) 2^{u_i}$$

This implies Problem 3 (Counting Reachable Sets) is in P for 2 column matrices.

Proof. It is clear that we can look at each component of the bipartite row element graph separately. Consider the case that component i is a tree. We know from the proof of Theorem 13 that every proper subset of E_i is reachable, i.e., at least one element must not be chosen. These are $2^{a_i} - 1$ subsets. From the unavoidable elements all subsets can be chosen. Consider now the case that component i has a cycle. Then we know that all elements from this component can be chosen at once. This leads to $2^{a_i+u_i}$ reachable subsets. As the choice is independent for each component, we take the product. \square

Theorem 15. *Problem 4 (Counting Exactly Reachable Sets) is #P-complete already for 2-column matrices.*

We will show #P-hardness for 2-column matrices. By adding $k - 2$ columns each consisting of a single new element we get a k -column matrix with the same number of exactly reachable sets. Thus the problem is also #P-hard for k -column matrices with $k \geq 2$.

Proof. We reduce the problem from the #Independent Set Problem, which is #P-complete. This is the problem of counting the number of independent sets in a given graph. Membership in #P follows from the exponential bound (2^{m^2}) on the number of exactly reachable sets. More on the complexity of counting independent sets in a graph can be found in [19, 10].

Let $G = (V, E)$ be some connected graph. We construct a two column matrix M_G with the property that non-empty independent sets are in one-to-one correspondence with exactly reachable sets. The elements of M_G are the edges and the vertices of G . For each edge $e = (u, v)$ we insert two rows (e, u) and (e, v) . This implies, that the edges are unavoidable and for every edge e at most one of its vertices will be selected in the two rows corresponding to e .

Let $W \subseteq V$ be some non-empty independent set. The set X_W is defined as $X_W = E \cup (V \setminus W)$. We show: X_W is exactly reachable. We do this in three small steps. First we define an orientation on G . Then we define a permutation π on M_G . At last we will argue that the greedy matching τ_π defined by π selects exactly X_W . Let T be some spanning tree of G and let x be any element in W . We orient every edge away from x in T , to get an orientation O_1 on T . Note except for x every vertex has indegree 1 in T .

We construct O_2 from O_1 by changing the orientation of each edge incident to W such that the in-degree of every vertex in W is zero and orient every remaining edge in G arbitrarily. For this orientation holds $v \in W$ if and only if $\text{indegree}(v) = 0$.

Let π be any permutation such that the following holds: for every edge $e = (u, v)$ oriented towards v , row (e, u) is before (e, v) in π . This implies that the vertices not selected by τ_π are exactly those with in-degree zero. This shows X_W is exactly reachable.

Conversely, let X be some exactly reachable set. All edge elements are unavoidable, thus are in the set X . Further the vertex elements W not selected form an independent set in the graph. To see this observe that two adjacent vertex elements cannot be avoided simultaneously. Note that W can be empty.

We have shown that every non-empty independent set W in G corresponds to an exactly reachable set X in M_G . Note that the empty set is also independent in G and would correspond to $X = E \cup V$. Note $E \cup V$ is not necessarily exactly reachable, but we can easily check if this is the case. (We leave it as an exercise to check that this is the case whenever G is a tree.)

Thus the number of exactly reachable sets equals the number of independent sets, maybe minus 1. And we can determine efficiently if this “minus 1” is the case. \square

This last theorem also implies #P-hardness of Problem 5 (Counting Exactly Reachable Supersets) for 2-column matrices with $D = \emptyset$.

5 Multi-matchings and miscellany

Our notions about matchings can be generalized naturally to the case of *multi-matchings*, defined in the following way. Additional to A and B and the preference lists of members of A (i.e., M), we are given a list of prescribed degrees $L \subset \mathbb{N}$. For each $a \in A$ exists a degree $\ell_a \in L$ associated with a . We are interested in subgraphs of the complete bipartite graph between A and B where the degree of every a is exactly ℓ_a . Clearly, $\ell_i = 1$ for all i gives the case of matchings. This can be imagined such that each member of a has to be matched with ℓ_a members of B . In the matrix terminology it means that in row a we select ℓ_a positions. Note that in case of multi-matchings a matrix may have more than m relevant columns. In a given row r we say that a set of positions $P = \{p_1, p_2, \dots, p_{\ell_r}\}, p_1 < p_2 < \dots < p_{\ell_r}$ (a position is smaller than another if it is to the left of the other) is *better* than another, different set $Q = \{q_1, q_2, \dots, q_{\ell_r}\}, q_1 < q_2 < \dots < q_{\ell_r}$ (both of size ℓ_r) if $p_i \leq q_i$ for every i (and $p_i < q_i$ for at least one i). (Note that two sets of positions might be incomparable.)

A *blocking coalition* of a multi-matching τ is a subset A' of A such that there exists a multi-matching τ' that differs from τ on all elements of A' and the selected set of positions is better in τ' than in τ on A' . If there exists no blocking coalition (resp. of size i), we call the matching τ an *Pareto optimal multi-matching* (POMM) (resp. *i-POMM*).

A multi-matching τ is *greedy* if there exists a multiset permutation π of the multiset of rows in which each row $r \in A$ appears ℓ_r times, for all r , such that the multi-matching can be generated in the following manner: we process the

rows of M in the order determined by π , and in each step we pick the leftmost element in the current row that was not picked earlier.

First we show a general method how to generalize statements about POMs to statements about POMMs. Let (M, L) be a pair where M is a matrix with m rows and $L = (\ell_1, \dots, \ell_m)$ is the list of degrees. Let M' be the matrix with $\sum_{1 \leq r \leq m} \ell_r$ rows in which the r th row of M appears ℓ_r times. We can label the rows of M' by pairs (α, β) where $1 \leq \alpha \leq m$, $1 \leq \beta \leq \ell_\alpha$ (denote the set of all such pairs by S). The row of M' labeled by (α, β) is the β th occurrence of the α th row of M .

Lemma 16. *The sets and the elements that can be chosen by greedy matchings from M' are the same as the sets and the elements that can be chosen by greedy multi-matchings with degree list L from M .*

Proof. In a multiset permutation π of $[m]$, where r can be chosen ℓ_r times, replace the β th occurrence of α by the pair (α, β) . In this way $\tilde{\pi}$, a permutation of S , is obtained. The correspondence $\pi \leftrightarrow \tilde{\pi}$ is clearly a bijection (up to equivalence on permuting in $\tilde{\pi}$ the occurrences of copies of the same row).

It is clear from the definitions that the set chosen by π from M is equal to the set chosen by $\tilde{\pi}$ from M' . \square

Using this observation, our results about POMs can be easily generalized to POMMs. Recall that additional to A, B and M we are given a set of integers $L = (\ell_1, \dots, \ell_m)$ and in the definition of greedy-POMMs instead of permutations we regard multiset permutations that are sequences of rows which have length $\ell = \ell_1 + \ell_2 + \dots + \ell_m$ and contain row i as often as ℓ_i (the ℓ_i appearances of a given row are not necessarily consecutive in the sequence). Observation 6 and Lemma 7 generalize easily to this setting. Also, Theorem 2 can be generalized for this case. We summarize the generalization of the latter in the following theorem.

Theorem 17. *Given A, B, M and L as above. Let T be a set of k POMMs and $E(T)$ the set of elements selected by at least one multi-matching of T , then*

$$|E(T)| \leq \sum_{i=1}^{\min(k, m)} \left\lfloor \frac{\ell}{i} \right\rfloor.$$

We leave the proofs for the interested reader as they follow closely the corresponding proofs for POMs. For $k = m$ this theorem is again asymptotically tight (Example 8 remains trivially good, yet note that the asymptotics depends on L) and for fixed k and big m it is tight if $\ell_1 = \ell_2 = \dots = \ell_m$. Indeed, in this case the construction from Claim 9 below can be blown up such that for every element a in the example we introduce ℓ_1 new elements $a^1, a^2, \dots, a^{\ell_1}$ and in the example matrices we change every element a to the ordered list of elements $a^1, a^2, \dots, a^{\ell_1}$. This way the number of columns is multiplied by ℓ_1 . In the examples the relevant permutations are also blown up similarly, when in a step we would choose row r now instead we choose the same row r as often as

ℓ_1 . Note that in this case (when all ℓ_1 s are the same) this trick can be used in Example 8 as well, and the asymptotics become independent of L .

Theorem 4 can be generalized for multi-matchings as follows.

Theorem 18. *Let (M, L) be as before (M is a matrix with m rows, $L = (\ell_1, \dots, \ell_m)$ is the list of degrees). An element x of M is avoidable if and only if for every set R of rows of M , we have:*

$$|E(R)| \geq \sum_{r \in R} \ell_r.$$

Proof. This follows from Observation 16 and from the fact that the condition from this theorem for (M, L) is clearly equivalent to the condition from Theorem 4 for M' . \square

Finally (back to POMs) we mention some miscellaneous results that give some insight into the structure of matrices with the biggest number of different exactly reachable sets.

Lemma 19. *Let M be a matrix and e_1, e_2, \dots, e_k unavoidable elements. Further let M' be the matrix obtained by deleting e_1, e_2, \dots, e_k in M and appending k new columns to the left of M . The i -th column consists of the element e_i in every entry. Let E be an exactly reachable set of M , then it is an exactly reachable set also in M' . In particular $|\mathcal{E}(M')| \geq |\mathcal{E}(M)|$.*

Proof. Let E be some exactly reachable set and π some permutation for which $s(\tau_\pi) = E$. We modify π to σ by moving the rows that selected e_1, e_2, \dots, e_k to the beginning of the permutation. We claim that σ selects E in M' . Obviously, e_1, \dots, e_k are selected in the first k steps. Afterwards, σ behaves on M' exactly as π on M . \square

This means that we can transform every matrix, such that all the unavoidable elements are in the first columns, without reducing the number of exactly reachable sets. We show another transformation which does not reduce the number of exactly reachable sets.

Lemma 20. *Let M be a matrix, then there exists a matrix M' such that for any row the element in the last reachable position of that row does not appear anywhere else in the matrix and $|\mathcal{E}(M')| \geq |\mathcal{E}(M)|$.*

Proof. We achieve one by one for each row that the element in the last reachable position in that row does not appear anywhere else in the matrix. Say, in a row r the element e in the last reachable position p is not unique in M . We get M' by simply changing e to some new element e' in position p . Now for some permutation π , $s(\tau_\pi)$ either remains the same in M' and M or not.

In the latter case τ in M must choose position p . We claim that it cannot happen that after choosing p , τ chooses a position in some other row which has element e to its left. Indeed, in this case take the first such row r' after r in π . If we exchange r and r' in π , we get a permutation π' such that the

corresponding matching τ' chooses in M the element next to the right to p . This is a contradiction as p was a last reachable position. This implies that τ chooses exactly the same positions in M and M' and thus also the same elements, except that in M' it chooses e' instead of e .

Summarizing, for every image set I in $\mathcal{E}(M)$ either I is also in $\mathcal{E}(M')$ or I' is in $\mathcal{E}(M')$, where we get I' by changing e (which must be in I in this case) to e' in I . As e' is a new element, for different image sets I_1, I_2 this way we get different image sets I'_1, I'_2 , thus $|\mathcal{E}(M')| \geq |\mathcal{E}(M)|$. \square

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References

- [1] David J. Abraham, Katarína Cechlárová, David Manlove, and Kurt Mehlhorn. Pareto optimality in house allocation problems. In Xiaotie Deng and Ding-Zhu Du, editors, *Algorithms and Computation, 16th International Symposium, ISAAC 2005, Sanya, Hainan, China, December 19-21, 2005, Proceedings*, volume 3827 of *Lecture Notes in Computer Science*, pages 1163–1175. Springer, 2005.
- [2] Sanjeev Arora and Boaz Barak. *Computational complexity: a modern approach*. Cambridge University Press, 2009.
- [3] Haris Aziz, Felix Brandt, and Markus Brill. The computational complexity of random serial dictatorship. *Economics Letters*, 121(3):341–345, 2013.
- [4] Haris Aziz and Julián Mestre. Parametrized algorithms for random serial dictatorship. *Mathematical Social Sciences*, 72:1–6, 2014.
- [5] Rinat Ben-Avraham, Matthias Henze, Rafel Jaume, Balázs Keszegh, Orit E. Raz, Micha Sharir, and Igor Tubis. Minimum Partial-Matching and Hausdorff RMS-Distance under Translation: Combinatorics and Algorithms. In Andreas S. Schulz and Dorothea Wagner, editors, *Algorithms - ESA 2014*, volume 8737 of *Lecture Notes in Computer Science*, pages 100–111. Springer Berlin Heidelberg, 2014.
- [6] Péter Biró, Tamás Fleiner, David Manlove, and Tamás Solymosi, editors. *MATCH-UP 2012: the Second International Workshop on Matching Under Preferences*, Corvinus University of Budapest, Hungary, 2012.
- [7] Katarína Cechlárová, Pavlos Eirinakis, Tamás Fleiner, Dimitrios Magos, Ioannis Mourtos, and Eva Potpinková. Pareto optimality in many-to-many matching problems. *Discrete Optimization*, 14:160–169, 2014.
- [8] Nadia Creignou and Miki Hermann. Complexity of generalized satisfiability counting problems. *Inf. Comput.*, 125(1):1–12, 1996.
- [9] David Gale and Lloyd S. Shapley. College admissions and the stability of marriage. *The American Mathematical Monthly*, 69(1):9–15, 1962.
- [10] Catherine Greenhill. The complexity of counting colourings and independent sets in sparse graphs and hypergraphs. *Computational Complexity*, 9(1):52–72, 2000.
- [11] Matthias Henze, Rafel Jaume, and Balázs Keszegh. On the complexity of the partial least-squares matching voronoi diagram. In *Proceedings of the 29th European Workshop on Computational Geometry (EuroCG)*, pages 193–196, March 2013.
- [12] John E. Hopcroft and Richard M. Karp. An $n^{5/2}$ algorithm for maximum matchings in bipartite graphs. *SIAM J. Comput.*, 2(4):225–231, 1973.

- [13] David Manlove. *Algorithmics of matching under preferences*. World Scientific Publishing, 2013.
- [14] Noam Nisan, Tim Roughgarden, Eva Tardos, and Vijay V. Vazirani. *Algorithmic game theory*. Cambridge University Press, 2007.
- [15] Günter Rote. Partial least-squares point matching under translations. In *26th European Workshop on Computational Geometry (EuroCG10)*, pages 249–251, March 2010.
- [16] Daniela Sabán and Jay Sethuraman. The complexity of computing the random priority allocation matrix. In Yiling Chen and Nicole Immorlica, editors, *Web and Internet Economics - 9th International Conference, WINE 2013, Cambridge, MA, USA, December 11-14, 2013, Proceedings*, volume 8289 of *Lecture Notes in Computer Science*, page 421. Springer, 2013.
- [17] Sandy Scott. *A study of stable marriage problems with ties*. PhD thesis, University of Glasgow, 2005.
- [18] Lars-Gunnar Svensson. Queue allocation of indivisible goods. *Social Choice and Welfare*, 11(4):323–330, 1994.
- [19] Salil Vadhan. The complexity of counting. B.S. thesis, Harvard University, 1995.